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Quaternary palaeogeomorphologic evolution of the Wadi Faynan area, southern Jordan

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Abstract
The Faynan area comprises a complex assemblage of deposits and landforms of varying nature, age and position in the landscape. The dominant facies are fluvial, slope and aeolian. At least eight palaeochannels are present at different heights within the Wadis Dana and Ghuwayr. Fewer terraces are preserved in the Wadi Faynan. Planated surfaces leaving lowgradient straths, rock-cut channels and fluvial deposits are all evident. The continuing drop in regional base level as a result of subsidence of the Dead Sea trough has driven incision and aided in the retention of many of the terrace deposits as they have been abandoned as the wadi systems have eroded downwards. Calcretisation has enhanced the preservation potential of many of the fluvial deposits. A large proportion of these deposits are comparable to those found in the modern wadi systems, and it is thought that they formed under arid conditions similar to those that exist today. Two of the terrace deposits appear to reflect slightly wetter conditions as they consist of finer grained, better sorted materials and display evidence of biological activity. There are at least four distinct alluvial fan and slope deposits that have formed at the edge of various mountain fronts. The fans have been entrenched to varying degrees and are likely to have formed at different times in the Quaternary, possibly when conditions were more humid or during periods of increased tectonic activity. Aeolian deposits indicate a marginally drier phase in the Late Glacial maximum and similar sediments of mid-Holocene age could either reflect increasing aridity at this time as has been suggested by Frumkin et al. (1991) and/or be a result of the increasing impact of humans on the landscape. Many of the deposits are beyond the age range of optically stimulated luminescence (OSL) and radiocarbon dating techniques, but a proposed stratigraphy is supported by some numerical dates on the younger deposits and associated archaeological artefacts.

Keywords: Jordan; Palaeogeomorphology; Palaeoenvironments; Quaternary; Radiocarbon; Luminescence dating

Introduction

The desertic environment around the Wadi Faynan is highly complex having been affected by significant tectonic and cyclical climatic changes over the last few million years. The evidence for past climatic conditions in the Levant that has been published is often conflicting; some researchers such as Bowman (1990, 1997) and Neev and Emery (1995) argue that the area was wet and cold (pluvial) during glacials and dry and warm during the intervening interglacials. Others believe that it was dry and cold during glacial phases, and the interglacials were wet and warm (e.g., Huckreide and Wieseman, 1968; Goodfriend and Magaritz, 1988). In the light of such disagreement, this current work focuses on the Quaternary deposits preserved within the Wadis Dana and Ghuwayr (Ghuweir) and the area around their confluence where these ephemeral rivers merge to form the Wadi Faynan (Figs. 1 and 2) to see if a palaeoclimatic history is identifiable. This paper has four broad aims: (i) to observe, map and describe the range of different Quaternary deposits present in the Wadi Faynan area; (ii) to establish the role of palaeoclimate on sedimentary deposition over the Quaternary; (iii) to ascertain whether it is possible to distinguish between the effects of climate vs. tectonics on geomorphological processes; and (iv) to provide a chronological framework to enable a reconstruction of the history of palaeoenvironmental changes and landscape evolution in relation to the Levant during the Quaternary

1. Environmental setting

The geology in the Faynan area ranges from Precambrian to Quaternary in age. The igneous rocks present are predominantly Precambrian and include the Fidan Granite Unit, which largely comprises aplite granite, quartz porphyry and syeno-granite (Bender, 1974), and the Ghuwayr Volcanic Suite, which is made up of basic green tuffs, pyroclastic fragments and basaltic lava (Rabb'a, 1994). Sedimentary rocks comprise Cambrian massive sandstones and dolomites as well as Cretaceous sandstones, limestones and dolomites. A variety of Quaternary terrestrial sediments is present, including the Shagur Formation (Bender, 1974) and, to the north of Faynan, the lacustrine Lisan marls around the Dead Sea (Abed and Yaghan, 2000). During the Quaternary, basaltic lava has been extruded at fault intersections in the mountains near to Dana village (Barjous, 1992). Barker et al. (1997, 1998, 1999, 2000) have been the first to attempt to understand the Quaternary history of the Wadi Faynan area since the construction of the geological maps (that include only very general descriptions of the main Quaternary deposits) by Barjous (1992) and Rabb'a (1994).

The study area lies on the eastern edge of the Dead Sea Transform fault system (Fig. 1), which separates the Arabian and African tectonic plates. This pullapart basin began subsiding in the Miocene (Abed, 1985, Neev and Emery, 1995), and since then, the basin has accumulated approximately 105 km of left-

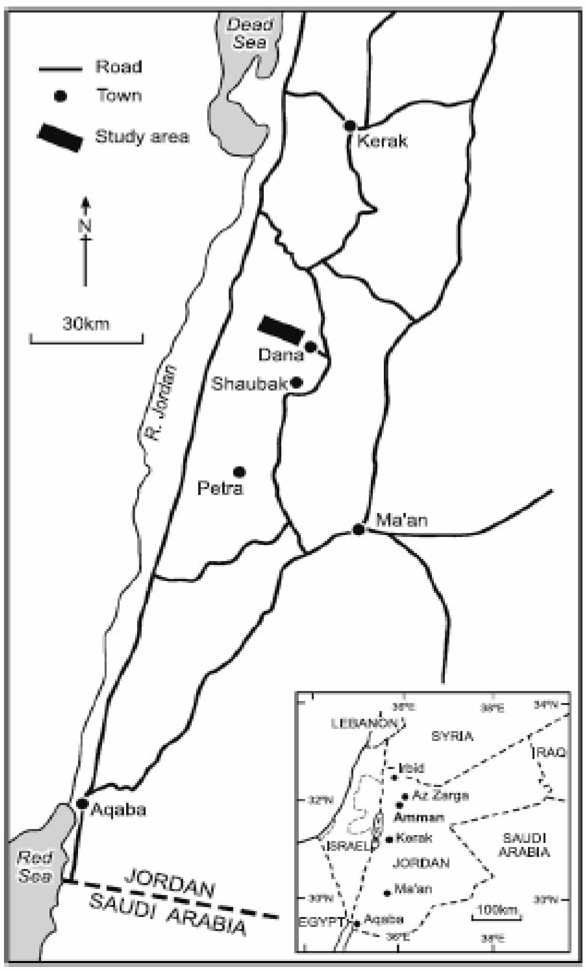


Fig. 1. Map showing the study area in relation to the Dead Sea Rift, and the inset indicates the location of Jordan with respect to its neighbouring countries.

lateral movement (Quennell, 1984) with an average geological slip rate of 5–10 mm/year^{-1} (Shapira, 1997). In the last 1000–1500 years, however, the slip rate has been slower at 1.5–3.5 mm/year^{-1} (Garfunkel et al., 1981). The eastern margin of the Dead Sea rift has been subjected to steeper downward faulting than the western side (Zak and Freund, 1981), and as a result, the area is structurally very complex. Two major faults that follow a general east–west direction bound a horst known as the Dana block (Rabb'a, 1994). These faults are thought to have been active during the Cainozoic (Barjous, 1992). There are also many small faults that display a variety of trends. Faulting in and around the Dead Sea graben, until recent geological times, has lowered the base level of the wadis that drain from the mountains to the west (Bender, 1974).

In addition to major tectonic activity, the late Tertiary saw climatic cooling. The start of colder and drier conditions in Jordan was in part a function of the collision of India with Asia causing the uplift of the Tibetan plateau in the Neogene (Zheng et al., 2000). This tectonic activity had significant effects on both regional and global climate, creating the easterly jet stream, which brought dry subsiding air to Arabia and North Africa (Raymo and Ruddiman, 1992; Ruddiman and Prell, 1997). In many areas of the Middle East, it is generally thought that arid phases occurred during glacial conditions in the northern hemisphere and more humid episodes were associated with interglacials. Such aridity occurred during glacials because the expansion of ice sheets at high latitudes and altitudes pushed the zone of westerly flow and cyclonic activity southwards to the latitudes of the Mediterranean and North Africa. Subtropical high-pressure regions were also displaced southwards, leading to an increased subsidence and enhanced aridity over the Middle East (Ruddiman and Prell, 1997). A steepening of the temperature and pressure belts between the poles and the equator also occurred leading to an increase in trade wind velocity, which Sarnthein (1978) argues resulted in greater aeolian activity in glacial dryland environments.

Research conducted in the Levant has resulted in some conflicting views on late Quaternary climate change (Fig. 3). Linvat and Kronfeld (1985) dated lake and travertine deposits from the Arava Rift valley in southern Israel using U/Th methods. Their results indicated that it was considerably wetter during the warm interglacial oxygen isotope stages (OIS) 5 and 7 but drier during the cooler OIS 6. Wet last interglacial conditions were also the finding of Moeyersons et al. (2002) who studied sediments, botanical and faunal remains in Sodeim Cave in the Red Sea Mountains in Egypt. Issar and Bruins (1983) have proposed that during the last glacial, rainfall was 50–100% more than that present in the Negev and Sinai. Macumber (1992) found sedimentary evidence around the Sea of

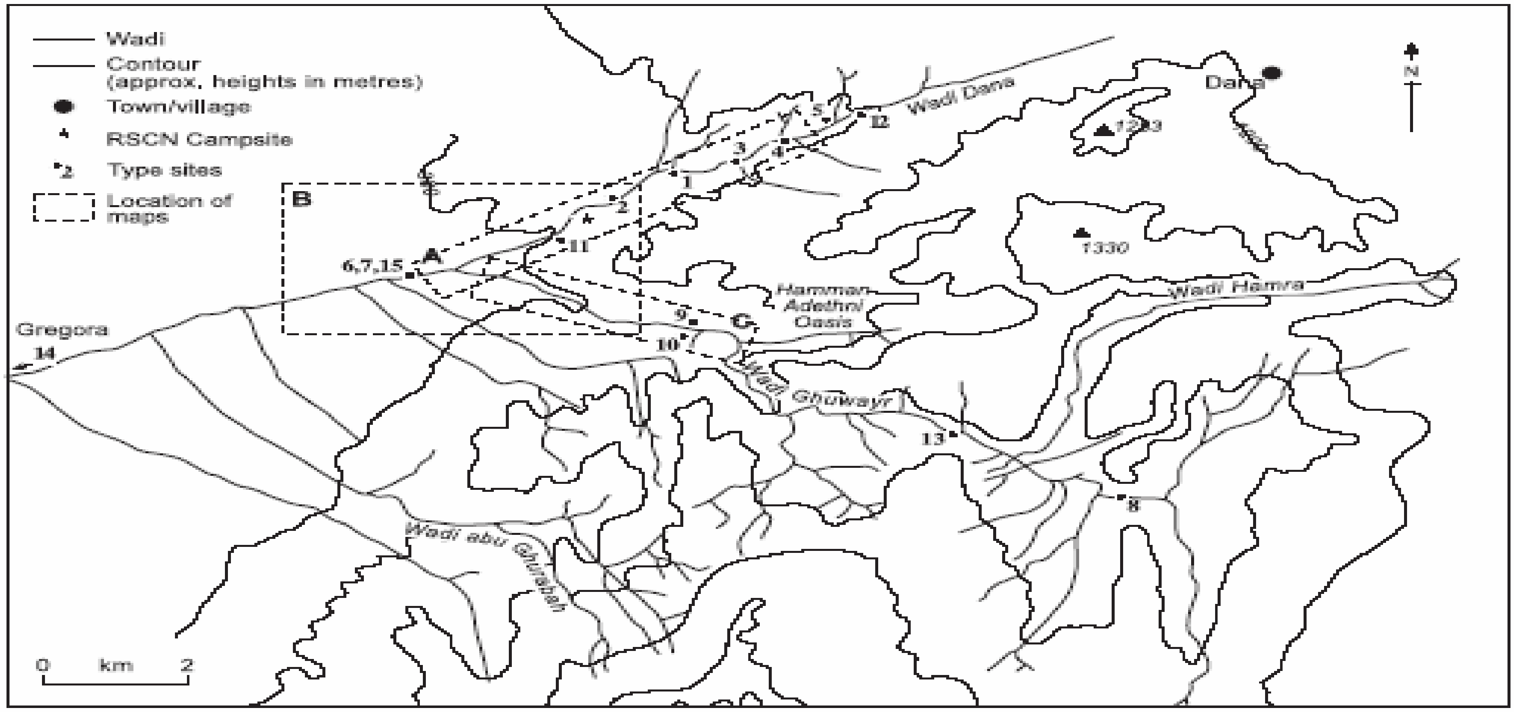
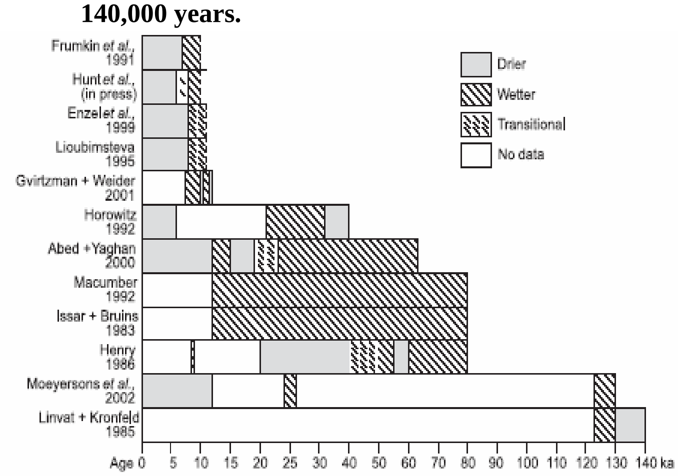


Fig. 2. Map showing the study area. The type sites referred to throughout the text are numbered 1– 15. Box A displays the location of Fig. 4 along the Wadi Dana; Box B shows the location of Fig. 7 around the confluence of the Wadi's Dana, Ghuwayr and Asheiair; and Box C locates Fig. 11 in the Wadi Ghuwayr. Type sites: 1=Quabbah Member; 2=Fass Yad Member; 3=Mokeim Member; 4=Dahlat Member; 5=Naqqazah Member; 6=Faynan Member; 7=Upper Dana Member; 8=Lower Dana Member; 9=Ghuwayr Beds; 10=Asheiair Beds; 11=Madrasah Beds; 12=Aqabah Beds; 13=Hamman Beds; 14=Gregora Member; 15=Tell Loam Member.

Galilee in northern Jordan for wetter conditions between 80,000 and 11,000 years ago. Henry (1986) has provided a more detailed climatic history for the Levant. Between 80,000 and 60,000 years ago lake, travertine and alluvial sediments have been interpreted as representing cool and moist conditions. It appears to have been drier between 60,000 to 55,000 years ago, as Lake Jafr dried up and gypsiferous marl was deposited (Henry, 1986). Geomorphic and palynological data from Wadi Hisma indicates that from 55,000 to 20,000 years ago, humid conditions gradually gave way to progressively drier ones. In contrast, Horowitz (1979), also working in Israel, proposed that it was arid between 40,000 and 32,000 years ago and then moist until 22,000 years ago. At Sodeim Cave in eastern Egypt, there is also evidence for wetter conditions before and around 25,000 years ago (Moeyersons et al., 2002).

Much of the late Quaternary palaeoenvironmental evidence in Jordan has come from studies of the lacustrine Lisan marls in and around the Dead Sea. Dated freshwater sediments indicate that Lake Lisan was in existence between 63,000 and 15,000 years ago (Abed and Yaghan, 2000). The Lisan marls are capped by gypsum, which represents the driest phase when conditions were brackish during the Late Glacial Maximum (LGM) between 23,000 and 15,000 years ago. Cooler temperatures during the LGM may have led to such a reduction in evaporation and atmospheric instability as to inhibit rainfall even in the zone of westerly cyclones (Nicholson and Flohn, 1980). There was a return to freshwater conditions between 15,000 and 12,000 years ago with the formation of the Damya Lake.

Fig. 3. Diagram showing published evidence for wetter and drier periods in the Levant over the last 140,000 years.



Not all researchers believe that the Dead Sea area dried out as a result of climatic change; Neev and Emery (1995) and Horowitz (1979, 1992), for example, argue that tectonic subsidence has played a major role. Abed and Yaghan (2000), however, oppose the idea of a dominant tectonic control as they claim that subsidence in the Holocene has been gradual and continuous at a rate of only about 0.83 mm/year$_{-1}$. In addition there are no major unconformities in the uppermost sediments, and the deposits that cross major faults do not show any signs of displacement. It is thought that conditions were drier in the Holocene with a brief moist phase between 9000 and 8500 years ago (Henry, 1986) (Fig. 3). Frumkin et al. (1991) have subdivided the Holocene sequence preserved in the salt caves of Mount Sedom in Israel into 10 climatic stages. Prior to 7000 years ago, there was a wet phase. Subsequently, it was generally drier with nine separate phases where it varied between being slightly drier than today to slightly wetter. Studying sediments and soils along the coastal plain of Israel, Gvirtzman and Wieder (2001) found evidence for a cold dry phase during the Younger Dryas between 12.5 and 11.5 ka; this was followed by a wetter phase from 11.5 to 10.5 ka. There was a return to dry conditions for 500 years before warm and wet conditions lasted from 10 to 7.5 ka. Subsequently, small-scale wet and dry fluctuations have occurred over the last 7500 years (Gvirtzman and Wieder, 2001). Moeyersons et al. (2002) describe the Holocene as being arid in absolute terms in the Red Sea Mountains. A drying of the Near Eastern, Asian and northern African regions is also thought by Lioubimsteva (1995) and Enzel et al. (1999) to have occurred from 8000 to 5000 years ago. Pollen studies from sites in Saudi Arabia, Palestine and Jordan contain assemblages consistent with steppe during a humid Early Holocene, with conditions becoming drier after 6000–5000 years BP (e.g., Horowitz, 1979; Fish, 1989; Baruch and Bottema, 1991; Van Zeist and Bottema, 1991). Within the Faynan area itself, research linked with this work by Hunt et al. (in press) looked at pollen, plant macrofossils and molluscs collected from various Holocene deposits. They have found evidence for slightly wetter conditions before 8000 years BP followed by a phase of desiccation between 8000 and 7400 years BP. By about 6000 years ago, Hunt et al. (in press) noted that pollen indicated a slight increase in rainfall, but there was notable decrease in the amount of trees, which they have argued is a function of increased human impact in the area. By the late Holocene, tree pollen was virtually absent, and a grass-dominated steppe assemblage existed. Frey et al. (1991) suggested, on the evidence of charcoal found in ancient smelting sites around Faynan, that major climatic oscillations occurred during later prehistory and into the historic period, but the patterns recorded could equally be a result of changes in wood procurement strategies. Archaeological and geomorphological evidence in the eastern Badia in Jordan (Allison, 1997) suggests that the region began to enter its present phase of aridity about 7000–5000 years ago, but detailed evidence of climatic change over this period in Jordan (and more specifically in the southern part of the country) is still lacking.

Today, the area is subjected to a dry desertic climate with an annual rainfall of just 50 mm per annum, although this rises to about 200 mm per annum on the upland plateau directly to the west of the study area. Southwest to westerly wind flows dominate during the winter months, and northwesterly flows are more common in the summer (Taha et al., 1981). Dust-rising and duststorms are very frequent in the Ghor and desert areas especially in the summer months with an average frequency of 25–60 days annually (Taha et al., 1981).

2. Methodology

The interpretations made are the result of extensive field walking and mapping along the wadis and the mountain front. A GPS has been used to locate areas of interest and an aneroid barometer utilised to help with altitudinal survey. The heights of the fluvial terraces have been measured from the base of the modern channel to the base of the exposure. Where sediments follow variations in the underlying geology or have overridden older (often cemented) deposits, there are some variations in height above the modern wadi. Relative estimates of age have been obtained by observing stratigraphic relationships. In general, the higher the abandoned relics of fluvial deposits on the mountain front or in the wadis, then the older is the deposit. The survey has identified both complex lithofacies relationships between deposits as well as issues of superposition. The complexity of the topography, the geological structure, slight variations in terrace height and movement of material due to gravity and tectonics have led to some uncertainty with interpretations, but the broad stratigraphy and geomorphological history of events proposed in this paper are thought to be valid.

Only the type sites (stratotypes) are described in any detail here, but maps show the distribution of the main stratigraphic units. This paper has adopted a nomenclature (much of which was first used in early publications on the fieldwork by Barker et al. 1997, 1998, 1998, 1999, 2000; Hunt et al., in press) that uses names that describe specific facies preserved within certain locations or at set heights in the study area. This is unlike the work of Finlayson et al. (2000) who concentrated on the confluence of the Wadi Faynan and use the same name to describe a range of different facies across their study area. Until the deposits are well dated and their contemporaneity can be assured, the present authors argue that different facies should be assigned separate names. Each facies can then be described separately allowing inferences about both processes and controls to be made. Site codes use the Faynan survey numbering system (Barker et al., 1997, 1998, 1999).

Numerical ages using optically stimulated luminescence (OSL) dating and radiocarbon dating techniques have been attempted. Samples for radiocarbon dating were taken from cleaned faces using steel trowels. The samples were dry when collected, and each was wrapped in aluminium foil and then bagged in selfseal polythene bags. At Beta Analytic, the samples went through a standard pretreatment where they were crushed in deionised water, washed firstly in hot HCl to remove carbonates and then in NaOH solution to remove secondary organic acids. Finally, the samples were rinsed to neutralise the alkali and then subjected to the standard radiometric dating procedure. Calibrated ages are shown as the 2r ranges flanking intercepts, since two or more intercepts are possible with most of the dates.

Dating using OSL measurements provides the time since the mineral grains within a sedimentary unit were last exposed to daylight. Samples for luminescence dating were collected by hammering plastic tubes into freshly cleaned sections. In the Aberystwyth luminescence laboratory, the sediment at each end of the tube that would have been exposed to daylight during sampling or transport was removed and used for measurements of the radioactivity of the material. A combination of thick-source alpha counting and beta counting were used to assess the radioactive dose arising from radionuclides of the decay series of uranium and thorium and from potassium. The contribution from cosmic rays was calculated on the basis of the depth of burial of the sediments using the equations of Prescott and Hutton (1994). Quartz grains 180–211 Am in diameter were extracted for luminescence measurements following treatment with HCl to remove carbonates and H_2O_2 to remove organics. Heavy minerals and most feldspars were removed by density separation using solutions of sodium polytungstate with specific densities of 2.58 and 2.62. Grains with a density between these values were then etched with 48% hydrofluoric acid for 40 minutes to remove any remaining feldspars and to etch away the alpha irradiated outer layer of the grains.

Optically stimulated luminescence (OSL) measurements were made on a Risø automated TL/OSL reader, using blue light emitting diodes (470 nm) for optical stimulation. The resulting luminescence emission was detected through two U-340 filters whose peak transmission is in the ultraviolet at 340 nm. The single aliquot regenerative-dose (SAR) procedure (Murray and Wintle, 2000) was used to assess the equivalent dose (D_e) from individual aliquots (f10 mg in mass) of each sample. Between 8 and 24 aliquots were analysed for each sample, and the mean D_e from these used to calculate the age (Table 1).

Recent reviews of the methods involved in luminescence dating of Quaternary sediments and examples of its application have been given by Duller (1996, in press) and Stokes (1999).

In the case of three samples (Aber18/JA2, JA9 and JA10) the luminescence signal was close to its saturation level—that is, the level at which the luminescence signal ceases to increase even when a sample is exposed to additional radiation. This saturation provides an upper limit for luminescence dating, and for these samples, the ages that are calculated are only minimum values.

4. Fluvial gravel ‘terrace’ members

4.1. Quabbah member, +125–130 m above the modern wadi floor

Type site: 5080 (30.6335N 035.516737E and 30.633525N 035.516739E), Wadi Dana (Figs. 2, 4–

Table 1
Dating results using OSL measurements

Lab code	Depth (m)	Beta dose rate (Gy/ka)[a]	Gamma dose rate (Gy/ka)[a]	Cosmic dose rate (Gy/ka)[a]	Total dose rate (Gy/ka)	Equivalent dose (Gy)	Age (ka)
Aber18/JA2	2.0	0.54±0.02	0.45±0.03	0.16±0.02	1.15±0.04	>125	>109
Aber18/JA3	3.0	0.51±0.02	0.44±0.03	0.15±0.02	1.10±0.04	60.4±2.0	55.2±2.8
Aber18/JA4	2.0	0.45±0.02	0.31±0.02	0.16±0.02	0.93±0.03	12.7±1.0	13.7±1.2
Aber18/JA5	1.5	0.50±0.02	0.34±0.02	0.17±0.02	1.02±0.04	13.9±0.4	13.6±0.6
Aber18/JA6	1.2	0.57±0.02	0.46±0.03	0.18±0.02	1.21±0.04	16.5±1.4	13.7±1.2
Aber18/JA7	6.0	0.34±0.01	0.37±0.03	0.10±0.01	0.82±0.03	48.1±2.5	58.6±3.8
Aber18/JA8	1.1	0.77±0.02	0.50±0.03	0.18±0.02	1.46±0.04	23.0±1.7	15.8±1.3
Aber18/JA9	5.5	0.39±0.01	0.39±0.03	0.11±0.01	0.89±0.04	>200	>225
Aber18/JA10	1.7	0.48±0.02	0.32±0.02	0.17±0.22	0.96±0.22	>200	>208

[a] Dose rate conversion factors are those of Adamiec and Aitken (1998). A water content of 2±2% has been assumed for all samples. The contribution from cosmic rays was calculated using the equations given by Prescott and Hutton (1994).

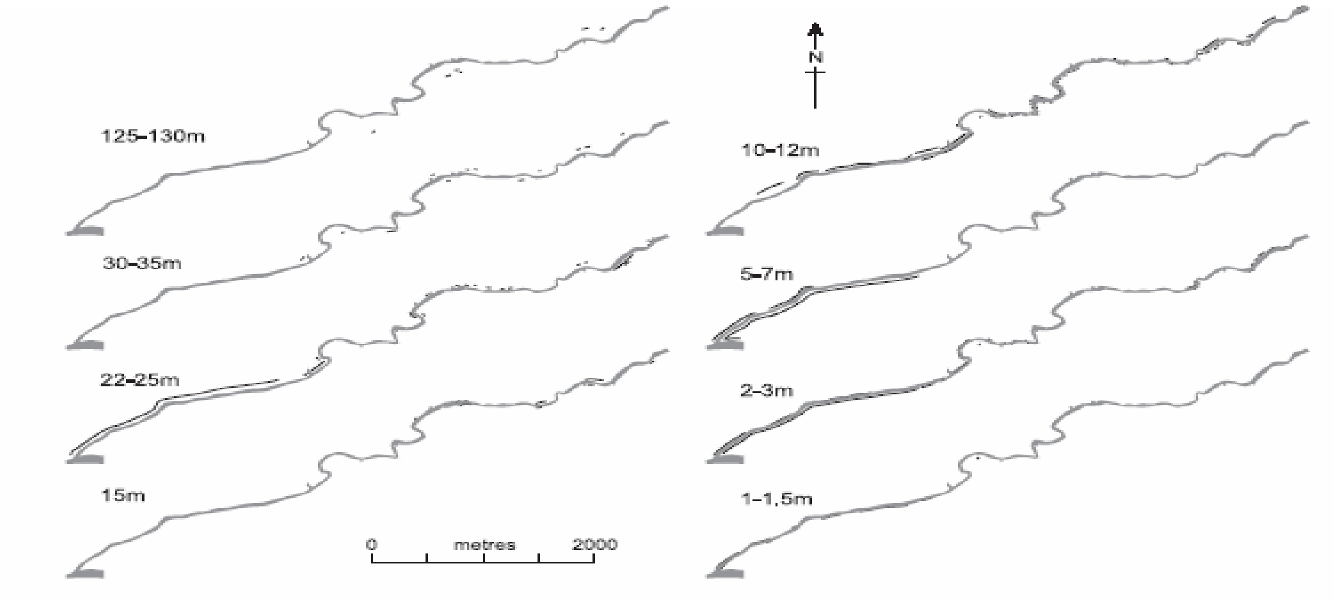


Fig. 4. The distribution of the main fluvial terrace deposits at various heights in the Upper Wadi Dana.

6). This deposit is exposed on some of the highest hills in the valley often in slight depressions on the hilltops. In most places, the Quabbah terrace is preserved as a loose boulder train unconformably resting on bedrock, although in the occasional location, it is preserved within a bedrock channel that trends in the same general direction as the modern wadi. In the latter situation the sediment has become calcretised. Where just a boulder train is preserved there is a matrix that is fine silt in nature, yellow in colour, and the material is unlithified. As a drape, it is found at various heights (typically between +110 and 130 m) above the wadi floor because it has been differentially eroded. In some areas, most of the sedimentary sequence has been preserved, whereas elsewhere, only the basal units remain. In places, the fluvial sediments appear to have been let down as the

bedrock has been eroded away, and often, there is clear evidence that some of the clasts have rolled downslope under the influence of gravity. Patches of this terrace are found at lower levels on the flatter plains beyond the mountain front (Fig. 7).

The deposit itself is poorly sorted with cobbles to huge boulders (some in excess of 2 m in length). The lithology of the clasts making up the deposit includes flint, limestone, two types of sandstone, granite and quartz pebbles, but there is a lack of basalt. Boulders stand proud on the surfaces and have clearly been there for a significant length of time as they contain well-developed varnish, solution pitting, exfoliation and cavernous weathering (Fig. 8). The boulders are generally rounded, although many have broken up into more angular fragments as a result of postdepositional salt and/or exfoliation weathering. The fluvially derived material has become mixed with weathered, angular fragments of locally derived bedrock colluvium. To date, no lithics have been found at this terrace height.

4.2. Fass Yad member, +30–35 m above the modern wadi floor

Type site: 5063; 30.63345N 035.500241E, Wadi Dana (Figs. 2, 4 and 5). At this site, there is almost 10 m of fluvial sands and gravels interbedded with up to three distinct slope deposits. The deposits sit within a rock channel cut through aplitic granite that is at least 30 m wide and may be up to 30 m deep. The basal unit of the channel sediments is about 3 m thick, and it rests on an eroded subhorizontal surface, where there is a sharp unconformable contact between the Pleistocene sediments and the igneous rocks. Rounded boulders of granite, limestone, sandstone and minor amounts of basalt are up to about 1 m in length. There are also angular boulders of locally derived bedrock present, and these probably represent intermixing of angular slope material with the fluvial sediments. The larger clasts are generally clast-supported, with a matrix of grey-brown silt.

The unit overlying the basal deposit is up to 10 m thick, but the lower part has been obscured by later collapse. The lowest visible unit consists of 3 m of rounded, imbricated limestone pebbles to boulders.

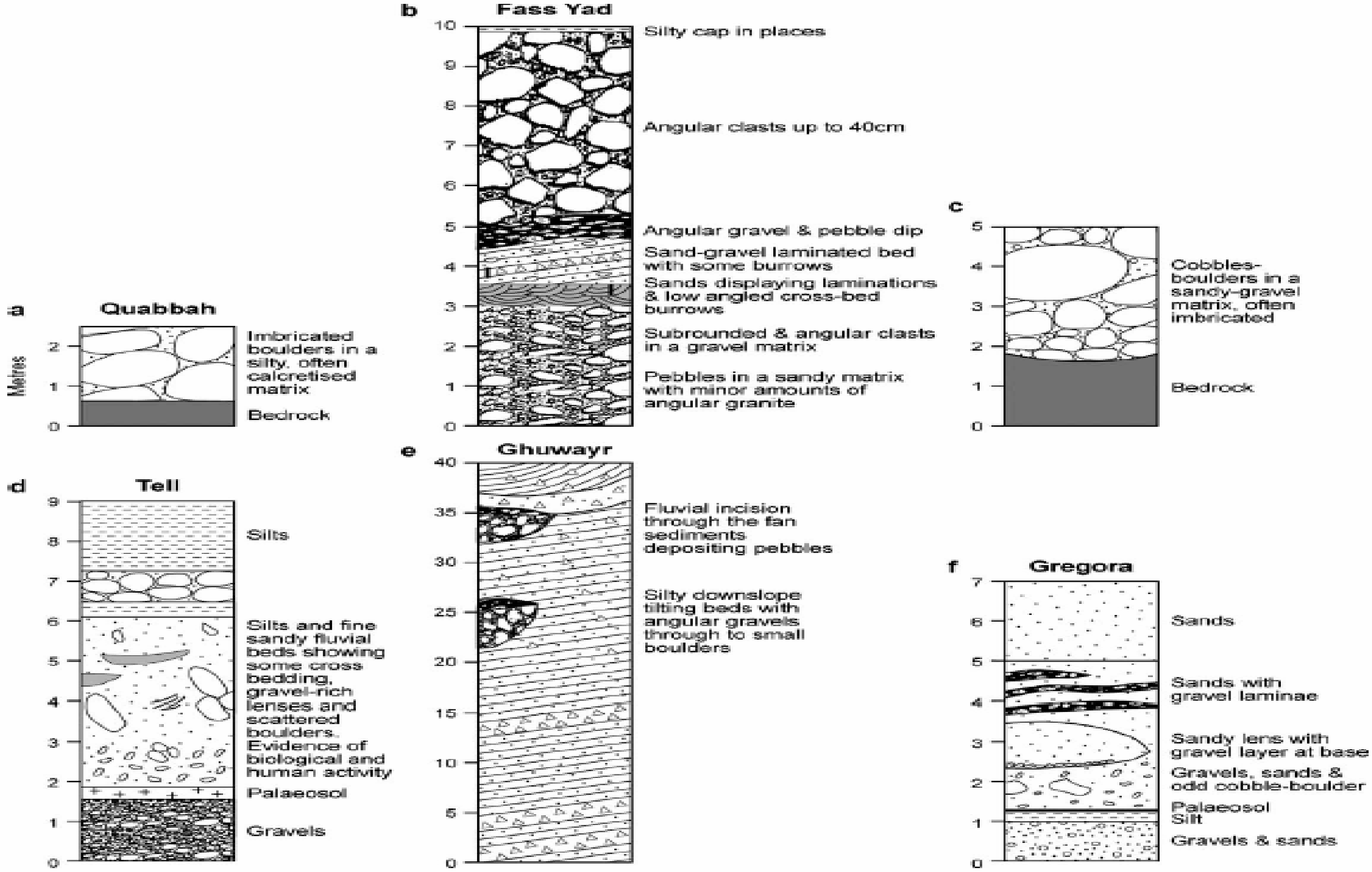


Fig. 5. Schematic sedimentary logs of (a) the Quabbah Member (+125– 130 m); (b) the Fass Yad Member (+30 m); (c) the Mokeim (+22– 25 m), Dahlat (+15 m) and Naqqazah (+10– 12 m) Members; (d) the Faynan and Tell Loam Members; (e) the Gregora Member.

The deposit is clast-supported with a matrix of fine pale brown sand. In places, there are layers of powdery tufa or calcrete, which possibly represent a former site of ground water seepage. Incorporated within this deposit are angular clasts of granite up to 40 cm in length, which appear to be locally sourced colluvium from the adjacent hillside, intermixed with the fluvial sediment. The upper part of this second unit has a layer of limestone boulders that show signs of weathering. These boulders are well rounded, up to 40 cm in length and are well imbricated, dipping upstream at an angle of 18–20j, at 45jN. They form poorly defined coarse boulder layers 30–50 cm thick with a sand matrix and the layers dip at 10j below horizontal at 220j (i.e., downstream).

Overlying the boulder-rich unit is about 50 cm of well-sorted fine sands that form laminae that have an average thickness of 2–3 mm, sometimes disrupted by animal burrows. These laminae and associated sand bodies are dipping downstream at angles between 5j and 15j. The deposit is weakly cemented except in occasional layers where thin carbonate nodules are present. These alluvial deposits are intercalated with layers (approximately 15 cm thick) of angular clasts of colluvial granite, which are typically weathered and decomposing. An OSL date from the well-sorted fine sands was obtained. The luminescence signal in the sample was close to saturation, and hence, only a minimum age of >109 ka (Aber18/JA2) could be obtained, and the actual date of the sample may be older.

The next unit is between 0.4 and 1.5 m thick. Its upper surface is capped by a layer of rounded to angular clasts up to boulder size (40 cm) of basalt, sandstone, chert and angular granite fragments; all jumbled on a thin surface dipping at 20j below horizontal to the south. The matrix is sandy, and it has been substantially calcretised. This deposit appears to be a rock fall/debris flow from the sideslopes down the palaeoriver channel and onto the river bed. A hand axe was found lying flat-bedded within the sequence in this unit (Fig. 9). Its long axis was orientated normal to the presumed direction of movement, about 1 m below the contact between this unit and the overlying colluvium.

Unconformably resting on top of the last unit is about 5 m of very poorly sorted cobbles and boulders, which are typically angular and blocky, although some are rounded. The clasts often have a vertical

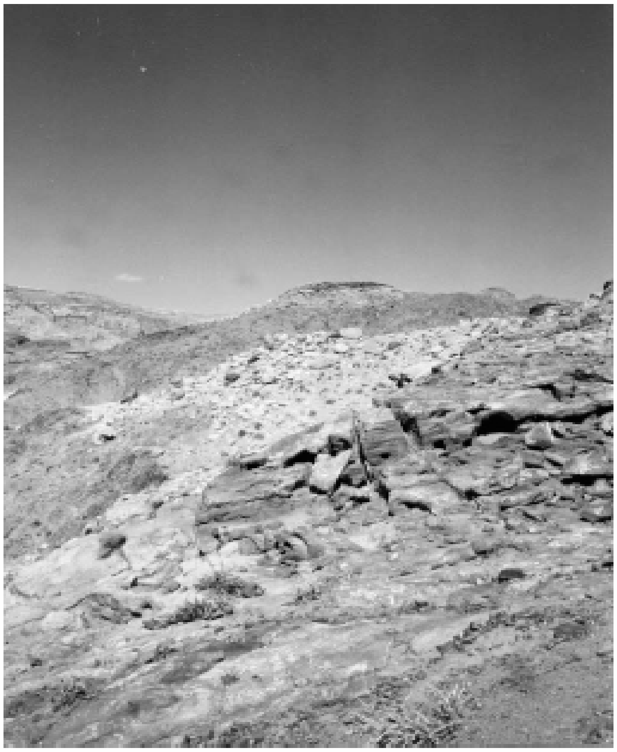
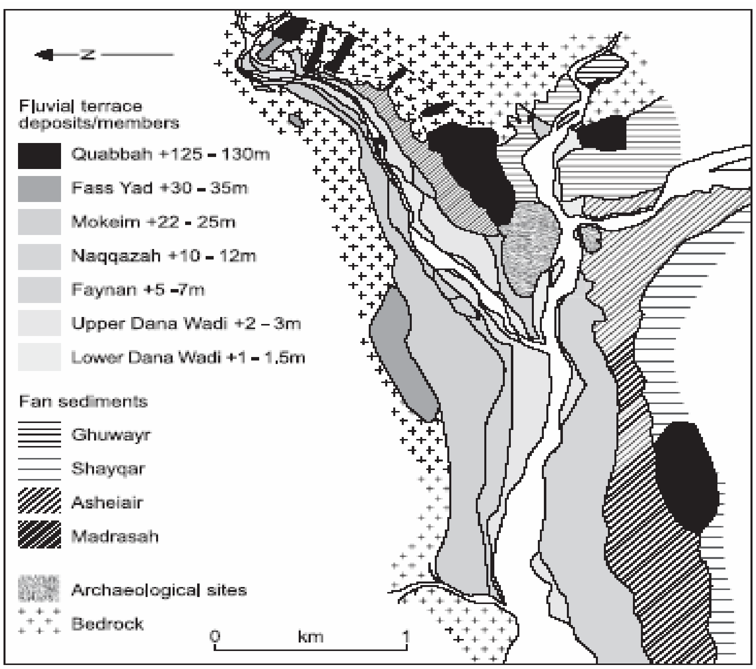


Fig. 6. Type-site: +125-m terrace, Wadi Dana–showing the poorly sorted but rounded loose boulders that make up the +125-m terrace on the mountain tops above the Wadi Dana.

Fig. 7. Quaternary sedimentary map of the area around the confluence of the Wadi Faynan.



or near-vertical orientation. These deposits are interpreted as a rock fall on to the stream edge. The deposit is matrix supported, and the beds are dipping downslope at 280j. The matrix is of fine sand, in places strongly cemented. Within and upon this deposit are cobbles and boulders (up to 1.5 m in length) of weathered well-rounded limestone and sandstone with extensive desert varnish. Some or all of these boulders may have been reworked and fallen from uphill. The colluvium is being eroded rapidly by rilling and sheet flow.

4.3. Mokeim Member, +22–25 m above the modern wadi floor

Type site: 5010; 30.633556N 035.516834E, Wadi Dana (Figs. 2, 4 and 5). This deposit has been left hanging on the side walls of the channel as the wadi has subsequently cut down to its current level (Fig. 10). The exposure displays a cross-section of the palaeowadi channel, which is a tributary that used to feed into the Wadi Dana flowing from north to south. It is a heavily indurated deposit with some Fe- and Mn-staining that infills a rock-cut channel. The clasts are often floating in a calcrete matrix, but the larger material does show grain-to-grain contact. The channel shows two phases of downcutting through the bedrock. There is an initial level that is less than 1 m deep and 45 m wide, and this was followed by a further incision of over 8 m deep in the central portion of the wadi. The width of this channel is about 23 m wide. A phase of infilling followed on after incision resulting in about 9 m of accumulated material ranging from sand-sized to boulders. The sediment is fairly poorly sorted but moderately well rounded. This sorting may be the result of the initial deposition of one massive boulder unit followed by the addition/infiltration of a finer matrix of sand and silts possibly washed in after a major flood event. To summarise, the base of the unit is fairly fine-grained, which coarsens upwards, and then the upper units are finer again. There is some bedding evident, and this is most clearly picked out by differentially cemented units (the finer grained beds appearing to be better cemented and less eroded back). There is a scattering of loose boulders on top of this unit along with angular slope debris. There is some evidence of imbrication of the clasts that comprise a wide variety of rock types including sandstone, limestone, basalt and porphyrit-
.
ic microgranite. Large blocks of fluvial conglomerate have broken away and fallen down into the modern wadi channel.

4.4. Dahlat Member, +15 m above the modern wadi floor

Type site: Transect C, Wadi Dana (Figs. 2 and 5). This terrace has an upper uncemented boulder train, and some of this loose material has rolled down to about 13 m above the modern wadi. The uncemented material is mostly clast supported, although there is some silty matrix present. The basal part of this unit is

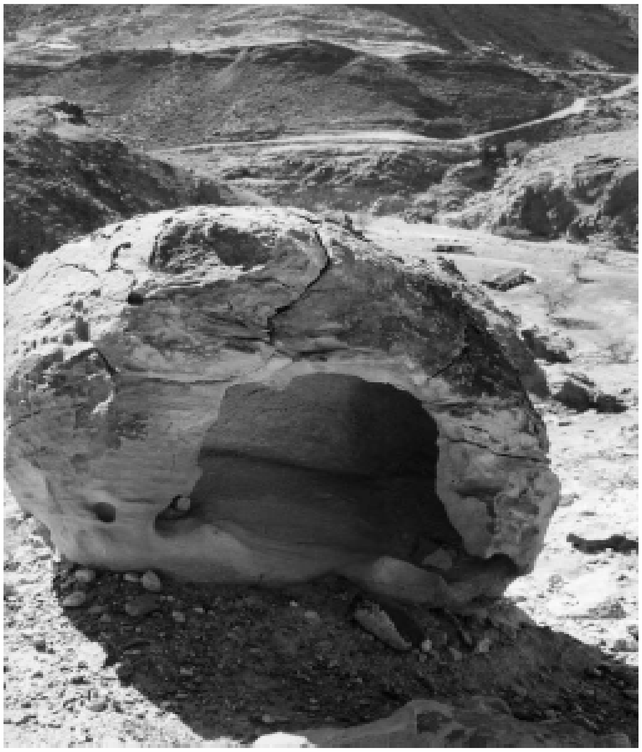


Fig. 8. Type site: +125-m terrace, Wadi Dana, heavily weathered boulder showing significant cavernous development.

calcreted and is about 1 m thick. Where the deposit rests on bedrock it is cemented, and the clasts are supported by a fine yellow matrix. The material is predominantly bouldery in nature, and some clasts show evidence of imbrication.

At the type site, there are boulders, pebbles and cobbles spread across the surface from about 20 m down to the modern wadi channel. The higher boulders may represent remnants of an uncemented +22-m terrace deposit that have been affected by gravity. Rounded limestone, sandstone and basalt along with angular local quartz porphyry are all present, indicating that the deposit contains a mix of alluvial and colluvial deposits at this site. **Fig. 9. Type site: +30-m terrace, Wadi Dana, hand axe found in situ. Note the fairly poorly sorted but moderately rounded**

sediments

4.5. Naqqazah member, +10–12 m above the modern wadi floor

Type site: 30.653028N 035.536E, Wadi Dana (Figs. 2, 4 and 5). Here, the 10-m-high terrace deposit is up to 4 m thick. On the northern side of the Wadi Dana, the deposit is quite well indurated, but there is one place on the southern side where there is an uncemented unit that is between 8 and 11 m above the wadi floor (some material having moved downslope). The deposit ranges from sands to small boulders with distinct bedding and four fining-up sequences. Each bed appears to be fairly well sorted. The deposit is capped by a scattering of uncemented boulders that are rich in locally derived limestone.

4.6. Faynan Member, +5–7 m above the modern wadi floor

Type site: 5020; 5021; 30.62726N 035.47782E, Tell Wadi Faynan (with its neolithic buildings) (Figs. 2, 4 and 5). The Faynan Member rests unconformably upon 3–5 m of coarser yellow-brown trough crossbedded sandy gravels and pebbles. These sediments are similar to those that can be seen in the modern day wadi. Within the lowest unit, there is a soil horizon about 2 m below the base of the Faynan Member. This palaeosol is a prismatic soil that is iron enriched. The formation of a soil at this site indicates a stable land surface and possibly wetter conditions. The palaeosol shows laminations of silts and soils and are typical of over-bank sediments. The unconformable gravels below the Faynan Member are last glacial in age as they have yielded an OSL date of 58.6F3.8 ka (Aber18/JA7) at site 5020.

Above the lower fluvial sediments are epsilon cross-bedded pale-grey silts, with bones, worm tubules, ash, charcoal, pottery fragments, desiccation cracks (in the upper levels) and rhizoliths of reeds that are preserved within the deposits of a channel of a gentle stream (or a pond) that is about 8–10 m across. There are also clasts of compacted mud within the fluvial deposit that appear to be the old land surface that has been eroded and washed into the river. Near the top of the fluvial sediments is a pale brown silt that looks as if it has been deposited under conditions of low flow. These deposits infill a channel incised into Pleistocene gravels, and their upper part interfingers with anthropogenic deposits of the Neolithic site of Tell Wadi Faynan. The Tell site has been radiocarbon dated by Al-Najjar et al. (1990) to BP uncal. 6410F115 years (BP cal 7563 [7405, 7403, 7318] 7062) (HD10567) and BP uncal. 6360F45 years (BP cal 7418 [7269] 7164) (HD12335). In the Lower Wadi Dana, sediments from near the base of the Faynan Member have yielded an OSL age of 15.8F1.3 ka (Aber18/JA8), indicating that this deposit started forming in the last glacial. The lower

Fig. 10. Type site: +22-m terrace, Wadi Dana, hanging valley filled with calcretised fluvial material. The rock cut channel is highlighted by a line. Person on top of the channel sediments for scale.

parts of the Faynan Member contain coarser clasts that are similar to the sediments in the modern wadi, indicating similar conditions of formation to today.

4.7. Upper Dana Wadi Member, +2–3 m above the modern wadi floor

Type site: 30.631722N 035.491694E, Lower Wadi Dana and Wadi Faynan (Figs. 2 and 4). From the base, there is 190 cm of boulder-rich material fining up to medium gravel. Above this unit is a 20-cm-thick lens of trough cross-bedded unconsolidated sand. It is capped by 50 cm of sandy gravel (that are buff to pinkish-brown in colour).

4.8. Lower Dana Wadi Member, +1–1.5 m above the modern wadi floor

Type site: 30.614639N 035.533667E, Wadi Ghuwayr (Figs. 2, 4 and 11). Coarse pebbles are present at the base (about 20 cm thick) and are overlain by a 20-cm laminated sand lens and then 1.3 m of imbricated cobbles and small boulders. Trough cross-bedding is evident in places. The most recent phase of incision of the rivers in the area has resulted in the removal of much of the +1–1.5-m terrace. In places, the exposed surfaces of the sediment has become case hardened.

In the lower Wadi Dana, there are about 1.5 m of trough cross-bedded sands and gravels containing organic material, which has been radiocarbon dated to 390F50 years BP uncal. (Beta-115214); (AD 1430–1645 cal). Charcoal within Lower Wadi Dana Member fluvial deposits has been dated to 110F50 years BP uncal. (Beta-119600) (AD 1670–1950 cal). The fluvial deposits can thus be relatively securely dated to the very late Holocene. Some of the sediments are contorted probably as a result of an earthquake. Approximately 0.8 m of aeolian silts lie unconformably on top of this sediment. Resting upon the terrace and windblown silts are a number of wadi cross-walls.

5. Alluvial fan sediments

5.1. Ghuwayr beds

Type site: 30.62622N 035.50268E, Wadi Ghuwayr (Figs. 7 and 12). This unit is up to 40 m thick and consists of a mix of predominantly fluvial material with some debris flow deposits that abut against bedrock. The lower 1.5 m is slightly reddened in colour and comprises bedded and imbricated sands and gravels with a calcium carbonate-rich hardened crust on the surface. Above is about 2 m of poorly sorted silts to pebbles that are imbricated but not clearly bedded. This unit grades up into laminated fine silts and sands with darker gravelly laminations. Within this fan unit is the occasional lens of pebbles. The deposit varies laterally and changes from being dominated by slope processes upstream to containing more gravels and evidence of fluvial deposition downstream towards the Khirbet. Downstream, the material is made up of a wide variety of imbricated rock types including sandstone, limestone and various igneous rocks that are moderately rounded. It is generally uncemented and easily eroded with substantial gullying developed in places. Upstream, the fan material only contains locally sourced angular black igneous rock fragments. Bedding and laminations are distinct and these all indicate flow of material downslope from behind the Khirbet not from the Ghuwayr.

In a few places, there are a few clear channels cutting through the fan deposits, and these appear to be coming from down the Wadi Ghuwayr showing the interaction of slope and fluvial processes. These channel sediments are near the top of the Ghuwayr Beds at heights of approximately +20 and +30 m above the modern wadi cutting through the fans, but most of this material has been trimmed away by later incision of the Wadi Ghuwayr. The fluvial material contains rounded basalt, sandstone, limestone and

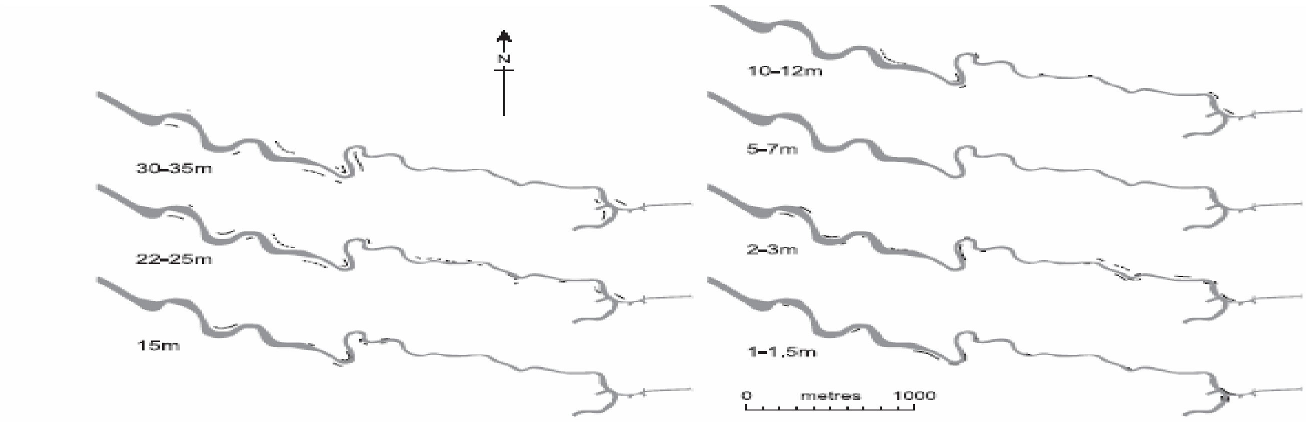


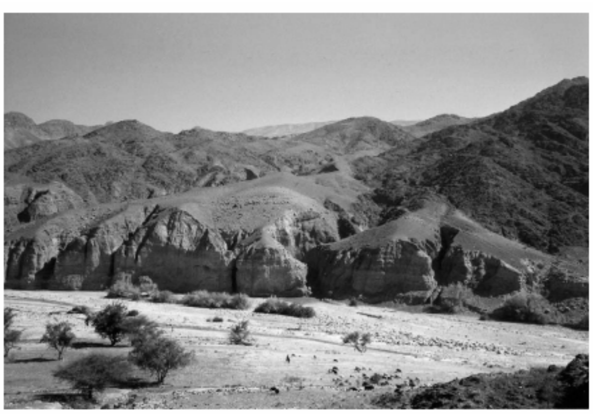
Fig. 11. The distribution of the main fluvial terrace deposits at various heights in the Wadi Ghuwayr.

flint and is clast supported. It is likely that these fluvial units postdate the fan sediments and that fragments were preserved as the Wadi Ghuwayr cut its way down through the Ghuwayr Beds until it obtained its current level. As the fluvial material gets eroded, it moves downslope and mixes with the colluvium. This intermixing is particularly evident in some of the gullies. A sample from 1 m above the level of the braidplain in the Wadi Ghuwayr was analysed using OSL, but since it was found to be saturated, only a minimum age of >225 ka (Aber18/JA9) could be obtained.

5.2. Asheiair beds

Type site: 30.616741N 035.483516E, (5027), Wadi Shayqar (Fig. 7). Exposed by the incision of the Wadi Shayqar are sequences of alluvial fan sediments, with a number of phases of activity evident. The size of the sediment is highly variable laterally, incorporating material from sands to large boulders in size. The beds vary between being poorly sorted bouldery debris flow deposits in some locations to areas with many clast-supported gravel-rich layers and sandy lenses, representing fluvially deposited alluvial fan sediments. The clasts point up towards the hills

Fig. 12. View of the Ghuwayr Beds looking across the Wadi Ghuwayr towards the northeast. The exposed sediments are sourced from the mountains behind rather than from the Wadi Ghuwayr that flows in the image foreground from right to left.



behind them not up the wadi channel. The lowermost 5 m is redder than the uppermost 5 m. The unit is generally capped by about 1 m of silt. An OSL date of 55.2F2.8 ka (Aber18/JA3) has been obtained from near the toe of the fan, indicating a last glacial age.

5.3. Shayqar beds

These sediments are not well exposed (hence, there is no type site), but their morphology as alluvial fans can be clearly seen both in the field and on aerial photographs (Fig. 7).

5.4. Madrasah beds

Type site: 5046; 30.637111N 035.506028E, Lower Wadi Dana (Fig. 7). In this area from the modern wadi floor to a height of approximately 6 m, there is a mix of slope wash and alluvial fan sediments. The basal 2 m comprises angular slope wash that is rich in the local aplite granite. On top is about 2.5 m of unconsolidated angular gravels and pebbles with silty clay and sandy lenses. There is abundant manganese staining of this unit. The top of this unit is unconformable, and overlying is a younger phase of fan deposition, comprising silty sands and gravelly layers that are about 1.5 m thick. An OSL sample taken from sediments exposed by incision of the Wadi Dana was found to be saturated, and hence, only a minimum age >208 ka (Aber18/JA10) could be obtained.

5.5. Aqabah beds

Type site: 30.653639N 035.538914E, Upper Wadi Dana (Fig. 2). Here, there are fans and other slope deposits coming off the southern slopes. In places, these slope deposits are interlayered with fluviatile sediments (particularly close to the modern Wadi Dana floor). There are about 3 m of a mix of slope wash and alluvial fan sediments exposed. This material comprises angular aplite granite, and it is generally in the size range of gravels to pebbles. In places, there is evidence of eroded remnants of the younger +10–12-, +5–7- and +3-m terraces cut into the fans.

5.6. Hamman beds

Type site: 5510; 30.618906N 035.516611E, Wadi Ghuwayr (Fig. 2). This site is about 3 km up the Wadi

Ghuwayr from Khirbet Faynan and about 2.5 km

downstream from the confluence of the Wadi Hamman and the Wadi Naheel. The sequence adheres to the steep slopes on the outside bend of a deep meandering river valley.

The slope of the land and talus towards the wadi floor at the site is in the order of 30j. There is a surface drape of colluvium and scree that in places is more than 10 m thick. The deposit appears to form a talus cone or fan that is made up of a poorly sorted breccia of angular sands, silts, pebbles and cobbles. The slope deposits rest on between 5 and 8 m of inter-bedded fluvial sands and gravels, with the occasional cobble layers. There are at least six separate flood events evident in the form of layers of boulderrich conglomerates of rounded large boulders and cobbles with sand matrix. Epsilon cross-bedding is evident. This deposit is discussed in more detail in Hunt et al. (in press). In addition there are 0.1–0.5-mthick layers of carbonate-rich and laminated marls, displaying load structures. Some of these marl units contain plant macro-fossils and tree leaves (there are abundant impressions of Typha and Phragmites leaves and stems). Accelerator radiocarbon dating was attempted on some oak leaves, but the sample was heavily contaminated with modern carbon (probably through micro-infestation) and was undateable (Beta-119601). Hunt et al. (in press) have placed the whole sequence in the Faynan Formation suggesting that the slope deposits unconformably overlie the fluvial deposit, which may be the case. However, the junction between the two deposits is unclear, and the fluvial deposits may be later and cut into the slope deposits. Therefore, for the purposes of this paper, the slope deposits are being treated as a separate unit and given a different name. Future studies may resolve this issue.

6. Aeolian deposits

6.1. Gregora Member

Type site: 30.616709N 035.416863N. Pumping Station near Gregora village. This deposit is about 5 m thick and consists of interbedded water lain gravels and well-sorted aeolian sands. The base starts about 3 m above the modern wadi, and here, there is about 20 cm of exposed gravels and pebbles; above is a thin silty horizon that grades up into a palaeosol. The next unit is 30 cm of bedded fluvial gravels with minor amounts of cobbles/boulders. This unit is followed by a sand lens that is up to 40 cm at its maximum thickness. Overlying is 25 cm of interbedded sand and gravel layers. The whole unit is capped by up to 3 m of windblown sand. Two OSL dates have been obtained, one from a fluvial unit in the middle of this exposure (13.6F0.6 ka; Aber18/JA5) and one from the centre of the upper aeolian unit (13.7F1.2 ka; Aber18/JA4). These dates suggest penecontemporaneous fluvial and aeolian activity in the area.

Exposures of windblown sediments on the hillslopes can be found predominantly on the south and east sides of the upper Wadi Dana (30j38V41.4N; 35j31V03.2E) about 1–2 km upstream of the Wadi Faynan RSCN camp. Up to 2 m of fine silt to sand that is grey to buff coloured can be seen. Sometimes, laminations are evident, trending in a downslope direction suggesting downhill water washing, and sometimes, the sediments are intermixed with colluvial screes. Occasional calcitic nodules are present.

The deposit is often found on lower angled surfaces, and it seems to have been eroded from many of the steeper slopes. In places, cutting through the silts and sands, there are a number of gullies that are up to 8 m wide and 1 m deep. These deposits represent windblown sediments that have been subsequently washed and eroded by surface water. This deposit has been OSL dated to 13.7F1.2 ka (Aber18/JA6), which is consistent with the age of the aeolian sands at the pumping station near Gregora.

6.2. Tell loam member

Type site: 5020; 5021; 30.62726N 035.47782E, Tell Wadi Faynan. This deposit comprises up to 2 m of slightly clayey silts with sands, subhorizontal desiccation cracks (palaeosurfaces), occasional gravel-filled scours and horizons of calcite induration and soft calcitic nodules. The surface of this deposit is deflating and is crossed east to west in a series of small loam-filled gullies which follow the natural dip of this deposit. The surface is up to 6 m above the modern wadi floor. The Tell loam rests upon a late Neolithic site at Wadi Faynan. It contains many walls and pottery fragments and is overlain by a deflating surface rich in Roman pottery. The Neolithic site has been dated to uncal. 6410F115 and 6360F45 years BP (Al-Najjar et al., 1990) as discussed earlier. Charcoal within the loams gave C-14 dates of uncal. 5740F35 years BP (BP cal 6654 [6499] 6412) (HD12377) and a further date from 1.05 m from the surface gave a date of uncal. 5375F30 years BP (BP cal 6278 [6191] 5999) (HD12336) (Al-Najjar et al., 1990). This deposit represents a mix of aeolian with some overland flow deposits.

7. Interpretation of palaeogeomorphological events

The geomorphological history of the Wadi Faynan area is complicated, but several major phases of evolution have been identified. Three main types of deposit have been recognised, namely, fluvial, slope and aeolian.

7.1. Fluvial events

A fall in base level over time has resulted in phases of wadi incision interrupted by more stable periods of sedimentation during flood events. Only relatively rare high-magnitude flood discharges are important in shaping the morphology of bedrock channels (Baker and Kale, 1998). Between floods, the deposits have been modified by processes of weathering, diagenesis, minor pedogenesis and movement downslope under the influence of gravity. Traces of these rivers exist in the form of rock-cut channels, sediments and erosion surfaces. At least eight distinct terraces are preserved at different heights both in the Wadi Dana and the Wadi Ghuwayr. The number of terraces is a reflection of both the magnitude and frequency of floods and the pattern of events between them (Schick, 1974). Commonly, the deposits have become heavily calcretised (particularly where the deposits have been preserved within an impermeable rock-cut channel), which has strongly enhanced their potential for preservation (see McLaren, in press). The fluvial terrace deposits present in the Faynan area are similar to those described by Maizels (1987) in the Wahiba Sands in Oman, Butzer and Hansen (1968) in the Egyptian Nubia and Nash and Smith (1998) in the Tabernas Basin in southern Spain.

In the Faynan area, the terraces are commonly found at similar heights in both the Wadi Dana and the Wadi Ghuwayr, suggesting continual subsidence of the Dead Sea graben. These terrace suites suggest that similar fluvial processes were operating in both wadis at roughly the same time. These findings differ from the work of Schick (1974), working in the Nahal Yael research watershed in Israel, who noted that terrace sequences often do not correlate within and between drainage basins because the flow events vary in space and time. It is unknown how many other terraces may have been obliterated by burial, lateral erosion or by gully and slope processes. Further north in the Dead Sea area low lake levels of the Holocene have resulted in rapid river incision producing a number of terraces that vary in height over more than 50 m (Frostick and Reid, 1989).

Finlayson et al. (2000) have identified a gravel deposit that they have named the Valley Gravel. However, its distribution is unclear on their map showing the terraces (Fig. 2, p. 2), and therefore, it is not possible to compare how this deposit fits in with the deposits described in this paper.

7.1.1. Quabbah Member (+125–130 m)

The oldest preserved terrace in the Wadi Dana may predate the Quaternary basalts as, unlike all the terraces lower down in the sequence, this rock type is lacking. This deficiency may indicate that (a) the basalt has preferentially weathered away after deposition;
or (b) the deposit predates the eruption and cooling of the basalt; or (c) the channel was not flowing across the area of basalt distribution at this time; or (d) when this fluvial material was being deposited, there was little basalt coming from its source area. Deposition would appear to have taken place under arid conditions probably similar to today as a result of fairly high-magnitude, low-frequency flood events. This interpretation is supported by the size of many of the boulders present (up to a few metres in length). Due to the height of this deposit above the present-day wadi, this deposit is likely to be early Quaternary or even late Tertiary in age

7.1.2. Fass Yad Member (+30 m)

The overall sequence implies the erosion of a rock channel, then its infilling with coarse cobbles and boulders followed by a decrease in stream power and the deposition of sands. Later on, the fluvial deposits become intermixed and then progressively buried in slope deposits. These sediments therefore appear to be the deposits of a large powerful stream massing very coarse materials in large bars downstream. The thick unit of sands, gravels and larger clasts along with evidence of biological activity suggests that the climate at the time this sediment was deposited was slightly wetter than today (semiarid to moderately arid). More moist conditions are supported by the activity of the slopes at this time and the intermixing of the fluvial deposits with debris flow sediments. A Middle Palaeolithic hand axe was found in situ. The large extent to which the basalt boulders are rotten may explain the lack of basalt in the upper terrace deposits of the Dana. A sample whose OSL signal was close to saturation (Aber18/JA2) suggests that the deposit is older than 109 ka.

7.1.3. Mokeim (+22–25 m), Dahlat (+15 m) and Naqqazah (+10–12 m) Members

These terrace levels are found patchily distributed in both the Wadi Dana and the Wadi Ghuwayr. Water would have been retained for far longer periods within the impermeable channels, gradual evaporation having led to the concentration of calcium carbonate in the waters until precipitation occurs.

These deposits are fairly similar in appearance to the +125-m terrace (although the boulder size is generally smaller), and thus, it would appear that they were deposited under an arid regime not unlike that which currently exists.

7.1.4. Faynan Member (+5–7 m)

The deposit lying unconformably below the Faynan member has been dated at 58.6F3.8 ka (Aber18/JA7) which puts it into the last glacial. At the base of this unit there are boulders that fine up to moderately well-sorted and stratified sediments with some evidence of cross-bedding. Boulders underlying the Faynan Member were deposited under fairly arid conditions separated by periods when the surfaces were stable for long enough for soils to develop. These soils represent wetter conditions near the base of this deposit. The sediments of the Faynan Member show a sequence of fining upwards. The coarser clasts at the base have been dated in the lower Wadi Dana to 15.8F1.3 ka (Aber18/JA8). The sediments are similar in size and sorting to those in the adjacent current wadi, indicating similar conditions of formation to today. This finding accords with Abed and Yaghan (2000), who also found evidence for dry conditions around the Dead Sea area at this time. The rivers that deposited the overlying fine-grained Faynan Member were low-magnitude rivers, of long duration under a semiarid environment. A stable floodplain environment existed with perennial water and notable biological production. This is evidence for wetter conditions in the early Holocene probably between 8000 and 9500 years ago, which had ceased before 6000 years BP. The biological studies conducted on these sediments by Hunt et al. (in press) fully support this argument. This wetter phase ties in with evidence from elsewhere in the Levant (e.g., Henry, 1986; Frumkin et al., 1991; Gvirtzman and Wieder, 2001).

7.1.5. Upper and Lower Dana Wadi Members (+3 and +1–1.5 m)

The cross-bedded late Holocene Dana sediments are fluvial, and similar to those occurring on the wadi floor today, they rest unconformably against the lower Faynan terraces. The material in these raised terraces is in general similar to the size of material in the modern wadi channel and so could have formed under conditions of flash flooding that occur today. Bull (1979) has proposed that during the Holocene in the deserts of the Middle East, precipitation decreased and/or temperature increased. On hillslopes, such changes would have reduced vegetation density, decreased infiltration rates and increased the area of bare ground, thus increasing sediment concentration and water runoff for a given rainfall event. Subsequent decrease in soil thickness and increase in exposed rock led to a decrease in sediment yield and a reduction in critical power, but to an increase in stream power as a result of valley fill deposition: the critical power threshold was crossed, and erosion began in the fill (Bull, 1979). This may explain the accumulation of the +3- and +1–1.5-m terraces followed by the subsequent incision ultimately down to the modern wadi floor.

7.2. Alluvial fan and slope events

The fans formed during periods of instability of the surrounding hillsides as a result of an increase in precipitation, a decrease in evaporation or tectonic activity. Factors affecting the rates of water and sediment supply are those controlling the hydrology and erosion rates within the mountain catchment including geology, topography, climate and vegetation (Bull, 1991).

7.2.1. Ghuwayr Beds

The Ghuwayr Beds are talus fan and braid plain beds that have been dated using OSL. Unfortunately, these deposits were close to saturation, and all that can be said about these deposits is that they are older than 225.000 years in age. These alluvial fans probably developed over significant periods of time, representing multiphase rather than short events. Palaeolithic implements from both the base and the top of the Ghuwayr Beds have been recovered by Barker et al. (1997). These artefacts were collected from within and upon alluvial fan sediments and have not come from a fluvial deposit as indicated by Finlayson et al. (2000). Pleistocene fluvial terraces and the Ghuwayr Beds are likely to have been penecontemporaneous. Fluvial boulder trains incised into the Ghuwayr Beds at heights of approximately +30 and +20 m suggests that these terraces postdate the main formation of the Ghuwayr Beds. Finlayson et al. (2000) assign these two fluvial deposits to the upper part of their Khalid gravels. As these deposits rest unconformably upon what we have termed the Ghuwayr alluvial fan sediments (Barker et al., 1997), they are younger than the fans just upstream from the Khirbet, but the length of time is unknown. In this paper, these two terraces have been assigned to the fluvial terraces that outcrop extensively in our study area at these two heights above the main wadi (i.e., the Fass Yad and Mokeim Members).

7.2.2. Asheiair, Shayqar, Madrasah and Aqabah Beds

These deposits are probably all largely Pleistocene in age. The Madrasah and Aqabah Beds are largely made of locally derived bedrock. An OSL sample from the Madrasah Beds was in saturation and suggests that the base of this deposit is older than 208 ka (Aber18/JA10). Moeyersons et al. (2002) and Linvat and Kronfeld (1985), working in southern Israel and Egypt, respectively, have both found evidence for wetter conditions during the last interglacial. The Aqabah Beds are probably late Pleistocene and have some preserved remnants of the +10–12-, +5–7- and +3-m fluvial terraces that are cut into the fans. Thus, it would appear that this fan deposit predates everything younger than the Naqqazah Member. Elevated fluvial terraces higher than 12 m are not found on the fan sediments on the south side of the Wadi Dana, but there are exposures on the north side. The fluvial sediments are likely to have been deposited on both sides of the valley originally (as is the case elsewhere in the Wadi Dana), but they have subsequently been reworked and/or buried by the fans that formed at a later date. The Asheiair sediments are a mix of fluvial and coarser debris flow deposits. An OSL sample has dated this unit to about 55 ka (Aber18/JA3), i.e., last glacial. A number of researchers have proposed that wetter conditions occurred in the Levant at about this time including Henry (1986) and Abed and Yaghan (2000). Middle Palaeolithic and younger artefacts, ancient field systems, structures and minor soil development have been found on the surface of these beds.

On toposequence evidence and the smaller amounts of later entrenchment, the Asheiair Beds appear to be considerably younger than the Ghuwayr Beds. The Shayqar Beds in this paper refer only to fan facies rather than both fan and fluvial deposits as reported by Finlayson et al. (2000).

The alluvial fan deposits suggest a moderate arid to semiarid climate. Thick units of beds of poorly sorted and poorly stratified cobbles and pebbles alternating with thin layers of sand are common. These sediments probably represent periods when floods were of moderate intensity and short duration.

7.2.3. Hamman Beds

There is evidence of at least six flood events followed by significant slope activity. The fluvial deposits present in the Wadi Ghuwayr are thought to be Holocene in age (see Hunt et al., in press for further details). These wadi sediments have either eroded into (as water flows around a steep bend in the channel) or are overlain by slope deposits. Both the fluvial and colluvial deposits indicate slightly wetter conditions compared to today.

According to Frostick and Reid (1987), tectonic activity is often held responsible for abrupt coarsening of alluvial fan sequences, and the role of climate is often neglected. In the Dead Sea rift, there are interdigitated lake and fan sediments with sharp boundaries between the deposits and no evidence of tectonic shock (Frostick and Reid, 1989). This led the authors to propose that the coarse alluvium is deposited by low-frequency, high-magnitude events due to the infrequent nature of rainfall in this arid environment thus indicating a climatic control. Klinger et al. (2003) have also looked at alluvial fan deposits and lake level fluctuations around the Dead Sea. They too have argued for a climatic rather than tectonic control on fan aggradation and fluvial incision, with deposition taking place after a wet phase that lasted until about 6.5 ka. A return to more arid conditions led to exposure and transportation of soils downslope following a reduction in vegetation cover. After the slopes were stripped, there was a phase of fluvial incision into the fan sediments. However, whether predominant aggradation is associated with more humid or more arid conditions is controversial. For example, Dorn et al. (1987) proposed that fan aggradation occurred during relatively humid periods of the Pleistocene in Death Valley. However, Wells et al. (1987) believed that phases of fan deposition were representative of time-transgressive changes in climate and related several depositional phases to the arid Holocene. Dorn (1988) argued that aggradation occurred from head to toe of the fans in more humid (i.e., semiarid) climates and that fan head entrenchment coincided with the glacial–interglacial transition when climate locally was becoming more arid. Williams (1973), working in Australia, suggested that the deposition/erosion balance depends on rainfall intensity, deposition being dominant when intensity is high in brief periods of water abundance. Dissection coincides with low stream discharge. More recently, Dorn (1996) has come to the conclusion that in Death Valley (and probably in many other arid areas), it is extremely difficult to separate climatic from nonclimatic controls on fan evolution, particularly because of the lack of chronological control on Pleistocene fans. This also appears to be the case in the Faynan area.

7.3. Aeolian events

The movement of silt and sand-sized material by the wind can be an important mode of entrainment and transportation in deserts. Increasing amounts of wind erosion may occur as a result of increases in the velocity of the wind. It also can result from exposing surfaces to erosion by the wind by decreasing the vegetation cover either naturally (as a result of changing climatic conditions) or as a result of various anthropogenic factors such as cutting down vegetation for clearing purposes, fuelwood or overgrazing (Barker et al., 1997, 1998, 1999).

7.3.1. Gregora Member

The availability of material to be blown about by the wind suggests fairly dry conditions with a lack of vegetation. In the Wadi Dana and near Gregora, evidence of aeolian activity at about 13,700 years BP may tie in with the evidence of increased dust discharge during the LGM from Central Arabia (Sirocko et al., 2000). The windblown silts from the Wadi Dana could represent remnants of evidence of a slightly drier climate. However, in terms of the deposit at Gregora, there is no strong argument for conditions much different from today as intercalated fluvial and aeolian sediments are currently evident around the small town of Gregora.

7.3.2. Tell loam member

In the Tell Wadi Faynan area, there is evidence of wetter followed by drier conditions during the Holocene. In the early Holocene, perennial streams were present with adjacent human settlements established on the floodplain. Henry (1986) has also found evidence for wetter conditions in the early Holocene between about 9500 and 8000 years BP. The windblown Tell loam unit in the Wadi Faynan suggests the onset of aridification and/or the effects of human disturbance after about 7400 years ago. Pollen indicates that by about 6000 years ago, the landscape had become a relatively treeless steppe, but perennial rivers were still apparent in the area that now underlies Tell Wadi Faynan (Barker et al., 1997; Hunt et al., in press).

The Tell site directly below the windblown sediment has yielded dates of uncal. 6410F115 and 6360F45 years BP (Al-Najjar et al., 1990). In addition, there are two dates from the loess at Tell Wadi Faynan from charcoal of uncal. 5375F30 and 5740F35 years BP at the base of the loam (Al-Najjar et al., 1990). This deposit represents a mix of aeolian and slope wash deposits. In Israel, thin coverings of dust are commonly redistributed by runoff shortly after aeolian deposition, and the sediments are subsequently

redeposited at slope bases as colluvium (Dan, 1990). This gradual drying up through the Holocene is supported by the work of Henry (1986), Enzel et al. (1999), Lioubimsteva (1995) and Hunt et al. (in press). Dust discharge from the Red Sea and East Africa increased at 9900 and 8800 ^{14}C years in association with an intensification of the southwesterly monsoon (Sirocko et al., 2000).

8. Summary and conclusions

Environmental changes of great magnitude have been detected in the Wadi Faynan area. In brief, from early to mid-Pleistocene, phases of erosion in the mountains and deposition in the study area led to the accumulation of alluvial fans and fluvial deposits. The highest terrace level preserved is at f+125 m above the modern wadi. Conditions at the time of formation appear to have been arid with high-magnitude/low-frequency events occurring depositing large boulders. The next clear terrace is at +30 m where low-magnitude rivers deposited sands and gravels. In addition, slopes were active at this time as is evident from the colluvium intermixed and covering the upper parts of the Fass Yad terrace. The age of this deposit is uncertain but is older than 109 ka. Conditions at this time were probably slightly wetter than today, i.e., semiarid. The base of the Madrasah and Ghuwayr alluvial fan sediments have been shown to be older than approximately 200 ka. The Ghuwayr and Madrasah Beds may be significantly older than this. The surface of these deposits was essentially stable during the Middle Palaeolithic, as numerous stone artefacts of this age have been found on top of this unit, and Palaeolithic tools were recovered from sediments at its base.

The presence of river terrace deposits on top of and cut into the Ghuwayr Beds at +30 and +20 m, respectively, suggests that downcutting by the Wadi Ghuwayr through the Ghuwayr Beds from such heights postdates these alluvial fans. The +20-, +15- and the +10–12-m terrace deposits are similar in appearance to those in the modern Wadi Dana and Ghuwayr and probably formed under similar climatic conditions as today. The Asheiair Beds were deposited in the last glacial, but the age of the Shayqar Beds is uncertain—on the basis of toposequence and the lack of significant entrenchment, these deposits appear to be younger than the other alluvial fan sediments in the area. Middle Palaeolithic artefacts have been found on the surface of these units.

The Aqabah Beds have not been dated as yet. They are likely to be mid-Late Pleistocene in age as wadi terraces as high as +10–12 m above the modern wadi can be seen trimming the fan deposits. The fans therefore predate the formation of these terraces.

After the LGM, windblown sediments in the Wadi Dana have been OSL dated to 13.7F1.2 ka (Aber18/JA6), suggesting conditions that were favourable for aeolian deflation. Such dry conditions at this time have also been identified in the Dead Sea area by Abed and Yaghan (2000) amongst others.

The youngest fluvial deposits in the study area are the Faynan, Upper and Lower Dana Wadi Members. Dates on these deposits range from about 15,800 to

100 years old, and they seem to have formed under similar or slightly wetter conditions to now. Tell Wadi Faynan (Tell Loam Member) windblown sediments that are about 5500 years old indicate active aeolian entrainment, transportation and deposition in the mid-Holocene.

Trying to decouple tectonic and climatic controls on geomorphological processes in the Wadi Faynan area is difficult. Climatic change and, in particular, the lowering of base levels as a result of reductions in the level of the Dead Sea during glacial periods, may have played an important role. Bridgland (2000), however, argues that climatic forcing alone is insufficient to cause river terraces to form and that uplift is also necessary. Thus, the elevated wadi terraces could result from tectonic uplift of the mountains on the eastern side of the pull-apart basin. However, since the mid-Pleistocene, Zak and Freund (1981) have suggested that fault activity in the Dead Sea trough has been small. Such incision has left remnants of older rivers in the form of palaeowadi terraces.

In the Holocene, there is the additional complication of the effects of humans on the landscape. Removal of trees and vegetation by overgrazing or for land clearance, fuelwood, etc., can have similar effects to aridification that would result from a deterioration in climatic conditions; and it is difficult to distinguish between them.

Clearly, there are problems of correlating the various sedimentological units because of the lack of numerical dates, as most of the deposits are beyond the age limits of OSL and radiocarbon dating. Many units may be contemporaneous, but it is difficult to state this with any certainty. Dates obtained are not accurate or precise enough to correlate fluvial erosion, sedimentation or fan aggradation to Pleistocene climatic changes. The picture for the Holocene is a little clearer. Therefore, to date, it is necessary to be extremely cautious about grouping together different facies into set stratigraphic units (and thus indicating that the deposits are contemporaneous). Instead, the approach of using sedimentary facies (identifying distinctive sediments that have formed under certain environmental conditions reflecting a particular process or set of processes) has been adopted. With future developments in numerical dating techniques, it may be possible to resolve some of these issues.

The gravels survived because of rapid incision by the palaeowadi systems abandoning the deposits. Unless calcretised, any clay, silt and fine sand in the systems have often been removed after deposition by gravity, water and/or wind. The larger clasts have proved to be more resistant to erosion (and are too coarse to be deflated) and have largely remained in situ apart from the numerous pebbles, cobbles and boulders that have moved downslope under the influence of gravity. This has resulted in places in the introduction of older fluvial particles onto younger wadi terraces and the loss of clarity of the number of terrace levels.

The range of sedimentary deposits indicate that at various times in the past, climatic conditions have changed. Many of the fluvial terraces contain material that is similar to that found in the modern day wadi systems and are likely to have formed under comparable arid climates. Evidence for slightly wetter conditions comes in the form of perennial river deposits with evidence of biological activity, colluvium and probably alluvial fan sediments. Drier conditions around the LGM are evident from the aeolian deposits in theWadi Dana. Other windblown deposits in the mid-Holocene may either be a result of aridity or they may reflect the anthropogenic impacts on the landscape.

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